Double gate lateral IGBT on partial membrane*

Luo Xiaorong(罗小蓉)†, Lei Lei(雷磊), Zhang Wei(张伟), Zhang Bo(张波), and Li Zhaoji(李肇基)

(State Key Laboratory of Electronic Thin Films and Integrated Devices, University of Electronic Science and Technology of China, Chengdu 610054, China)

Abstract: A new SOI LIGBT (lateral insulated-gate bipolar transistor) with cathode- and anode-gates on partial membrane is proposed. A low on-state resistance is achieved when a negative voltage is applied to the anode gate. In the blocking state, the cathode gate is shortened to the cathode and the anode gate is shortened to the anode, leading to a fast switching speed. Moreover, the removal of the partial silicon substrate under the drift region avoids collecting charges beneath the buried oxide, which releases potential lines below the membrane, yielding an enhanced breakdown voltage (BV). Furthermore, a high switching speed is obtained due to the absence of the drain–substrate capacitance. Lastly, a combination of uniformity and variation in lateral doping profiles helps to achieve a high BV and low special on-resistance. Compared with a conventional LIGBT, the proposed structure exhibits high current capability, low special on-resistance, and double the BV.

Key words: SOI; LIGBT; on-resistance; breakdown voltage; switching speed
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1. Introduction

Silicon-on-insulator (SOI) technology offers tremendous advantages over bulk Si technology, such as superior isolation and low loss. However, SOI devices suffer from low breakdown voltages. Addressing the issue, several structures have been proposed[1−5], in which a variation in lateral doping profile on the thin SOI has been applied to achieve a high breakdown voltage (BV)[1]. Ultra-thin SOI membrane devices can increase the BV, but its current capability is limited and the junction temperature is high[6]. We also have reported a lateral double-diffused MOSFET (LDMOS) structure on partial membrane[7]. A lateral insulated-gate bipolar transistor (LIGBT) is one of several ideal options for high voltage and power applications due to its high breakdown voltage and high current capability. In comparison with LDMOS, the LIGBT has a low forward drop due to the conductivity modulation in the on-state and a long turn-off time caused by the minor carrier storage effect.

In this paper, a new SOI LIGBT with double gate on partial membrane (PM DG LIGBT) is proposed. Firstly, double gates lead to a fast switching speed and a lower specific on-resistance ($R_{\rm sp.on}$) in comparison to the conventional LIGBT. Secondly, the selective removal of the substrate under the drift region not only improves the electric field distribution in the SOI layer, but also cancels or at least reduces the drain–substrate capacitance and, therefore, enhances breakdown voltage and switching speed. Thirdly, a combination of uniformity and variation in lateral doping profiles helps to achieve a high BV and low $R_{\rm sp.on}$. Furthermore, the self-heating effect is alleviated because of the long silicon pillar and the low $R_{\rm sp.on}$ compared to the structure in Ref. [6].

2. Device structure and on-state characteristics

A cross section of the PM DG SOI LIGBT and its doping profile in the SOI layer are shown in Fig. 1. The Si substrate under the drift region is selectively etched. The buried oxide layer is used to share the vertical voltage and as an etch stopper. The device has double gates, called the cathode gate and anode gate. Moreover, the anode gate is extended over the drift region. The two gates operate independently, and the anode gate can be negatively biased in the on-state. The device has a combination of uniformity and variation in lateral doping (UVLD) in the

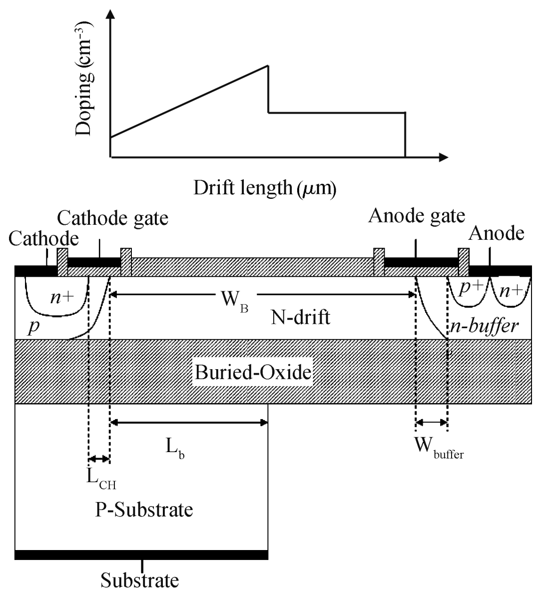

Fig. 1. PM DG SOI LIGBT structure and its doping concentration profile in the SOI layer.

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† Corresponding author. Email: xrluo@uestc.edu.cn

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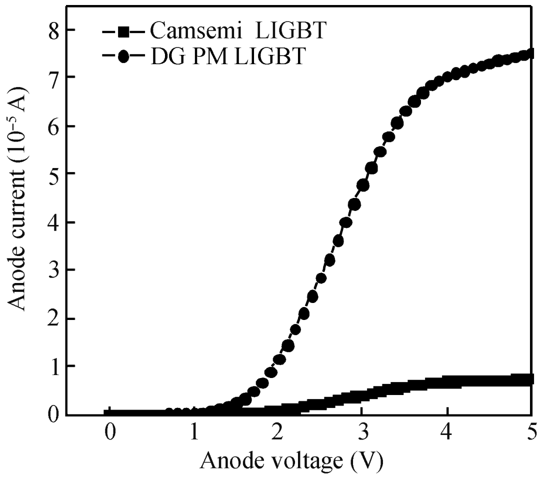

Fig. 2. Current–voltage characteristic in forward on-state (V_{Cg} = 5 V).

Table 1. Device structure parameters in simulation.

Parameter	Value
Device length	28 μm
Drift region length	17 μm
Thickness of SOI layer	0.5 μm
Thickness of BOX	3 μm
Thickness of the gate oxide	50 nm

drift region. W_B is the drift region width. L_b is the length of the Si pillar under the drift region and W_{buff} represents the width of the n-buffer, as illustrated in Fig. 1.

The forward on-state performances of the PM DG SOI, CamSemi, and conventional SOI LIGBTs are compared in Fig. 2. The simulation results in this paper are obtained by MEDICI and the structure parameters given in simulation are listed in Table 1. In order to have a fair baseline in simulation, the cathode gate voltage V_{Cg} is 5 V for all, and L_b= 0 for the PM DG LIGBT. The anode gate voltage V_{Ag} for the PM DG LIGBT is –5 V. The PM DG LIGBT has the highest current capability because of the greatest total charges in the SOI layer, while the current for the CamSemi LIGBT is the lowest due to its lowest doping concentration. The optimal concentrations in the SOI layer for CamSemi and the conventional LIGBTs are 7×10^{14} cm^{-3} and 1.2×10^{16} cm^{-3}, respectively. The total carriers in the conventional LIGBT are lower than that of the PM DG LIGBT. Moreover, the double gates help to increase the current capability for the PM DG LIGBT.

In this paper we use the bipolar transistor/MOSFET model to discuss the operating mechanism of the PM DG LIGBT. The saturation anode current is given by[8]

$$I_{C,sat} = \frac{I_{MOS,sat}}{1-\alpha_{PNP}} = \frac{1}{1-\alpha_{PNP}} \frac{\mu_n C_{ox} Z}{2L_{CH}} \left(V_{cg} - V_{th}\right)^2, \quad (1)$$

where $I_{MOS,sat}$ is the saturation electron current through the MOSFET, and L_{CH} and Z are the length and width of the channel under the cathode gate, respectively. C_{ox} is the gate oxide capacitance and V_{th} is the threshold voltage for the cathode gate. μ_n is the electron mobility . The PNP transistors have a large base width (N-drift region) in order to support the forward voltage. The current gain (α_{PNP}) is primary determined by the base transport factor; therefore, the current gain equation is given by[8]

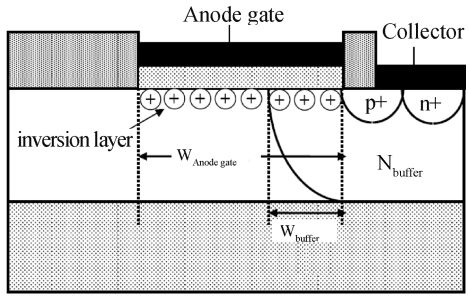

Fig. 3. Inversion layer under the anode gate at V_{Ag} < 0.

$$\alpha_{PNP} = \frac{1}{\cosh\left[\left(W_B + W_{buff} - W_{dpt}\right)/L_a\right]}, \quad (2)$$

where L_a is the ambipolar diffusion length. W_{dpt} is the depleted drift region width. W_{dpt} increases with increasing V_{Ag}, leading to the enhancement of α_{PNP}. The depletion layer does not extend into the N-buffer layer because of its high doping concentration. Therefore, saturation current is achieved, and α_{PNP} is expressed as

$$\alpha_{PNP,S} = \frac{1}{\cosh\left(W_{buff}/L_a\right)}. \quad (3)$$

Therefore, α_{PNP} becomes a constant.

For the PM DG LIGBT at $V_{Ag} < 0$, an inversion layer of holes is formed at the surface of the n-well and part of the n-drift layer as illustrated in Fig. 3. The inversion layer prevents the depletion layer extending to below the anode gate electrode, and the depletion layer only reaches the left edge of the anode gate electrode. So Equation (3) is written as

$$\alpha_{PNP,S} = \frac{1}{\cosh\left(W_{Anode\ gate}/L_a\right)}, \quad (4)$$

where $W_{Anode\ gate}$ is the length of the anode gate electrode. Because $W_{Anode\ gate} > W_{buff}$ (in Fig. 3), the saturation current of the PM DG LIGBT is larger than that of the single gate LIGBT from Eq. (1), as shown in Fig. 2.

The drift region is in a high-level injection state during the on-state. Transport of electrons and holes in the drift region is described by the ambipolar transport equations as follows[9]:

$$I_N = \frac{b}{1+b} I_T + qAD_a \frac{\partial n}{\partial x}, \quad I_P = \frac{b}{1+b} I_T - qAD_a \frac{\partial p}{\partial x}, \quad (5)$$

where b is the ratio between electron mobility μ_n and hole mobility μ_p. D_a is defined as the ambipolar diffusion coefficient, written as $D_a = \frac{\mu_n D_p + \mu_p D_n}{\mu_n + \mu_p} \approx \frac{2D_n D_p}{D_n + D_p}$, where D_n is the electron diffusion coefficient in the p^+ region and D_p is the hole diffusion coefficient in the n-drift region.

The inversion layer results in a large hole concentration gradient nearby at $V_{Ag} < 0$. It helps to increase the hole injection efficiency and, therefore, a large current is achieved from Eq. (5). The simulated current–voltage characteristics are

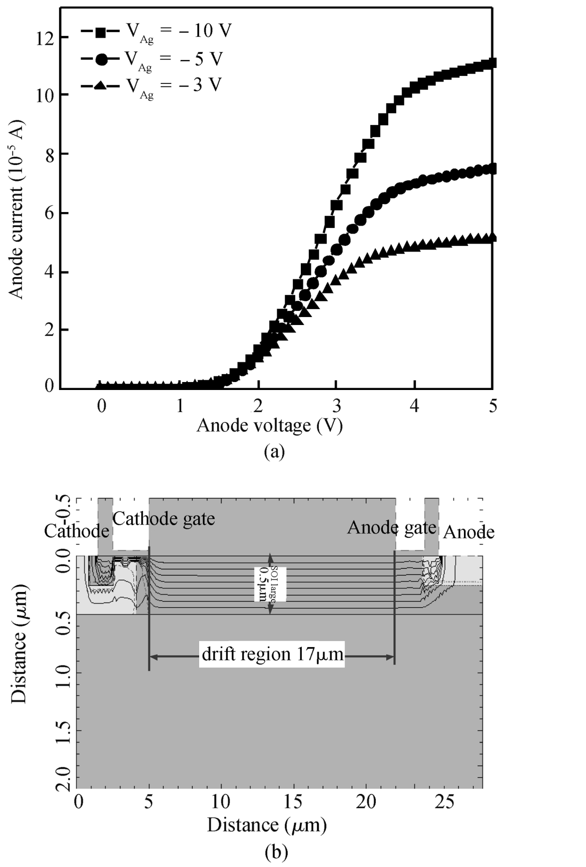

Fig. 4. (a) Influence of V_{Ag} on anode current in the forward on-state ($V_{Cg} = 5$ V, $L_b = 14\,\mu$m). (b) Flow lines ($V_{Ag} = -5$ V, $V_{Cg} = 5$ V, 10^{-5} A/line).

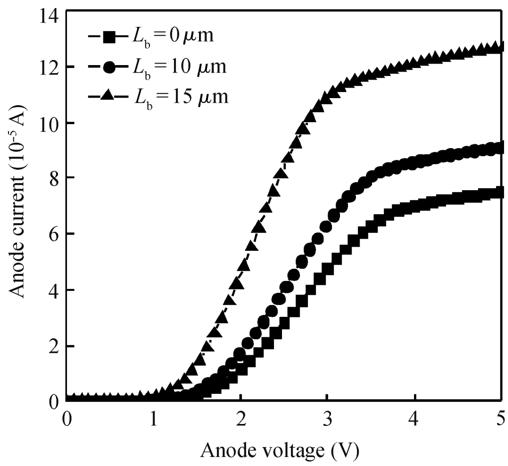

Fig. 5. Effect of L_b on anode current in the forward on-state (V_{Cg} = 5 V, V_{Ag} = –5 V).

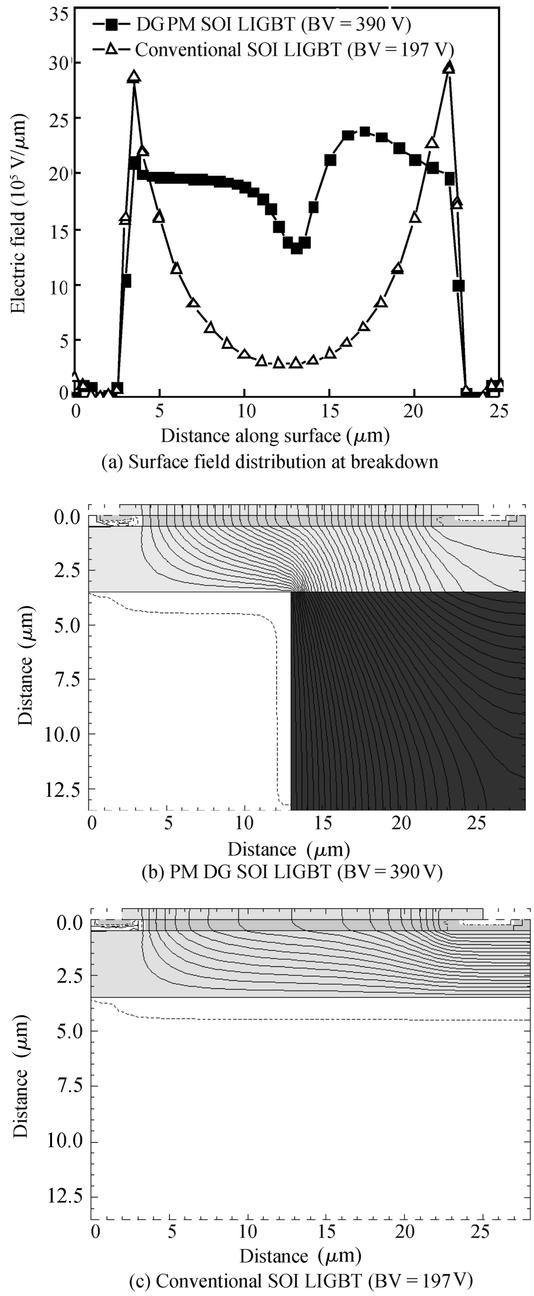

Fig. 6. Surface field distribution and the equi-potential contours at breakdown.

shown in Fig. 4. The saturation current enhances with the increase of the negative V_{Ag} because the hole concentration in the inversion layer and hole concentration gradient increase. Figure 4(b) gives the flow line distribution.

Figure 5 shows the influence of L_b on the anode current. It can be seen that the current capacity is enhanced with increasing L_b because the variation doping profile drift region over the substrate Si pillar can accommodate more carriers than the uniform doping profile in the membrane region; thus, the specific on-state resistance is reduced. However, the uniform doping section with the lower concentration does not help to reduce the on-resistance and enhance the current.

3. Blocking and thermal characteristics

The surface field distribution and the equi-potential contours for the PM DG SOI LIGBT are compared with those of the conventional SOI LIGBT in Fig. 6. For the conventional SOI LIGBT, there are two surface field peaks at the pn junction and the n^+n junction where premature breakdown is apt to occur, while the electric field in the middle of the drift region is low. However, both the surface field and potential contours in the SOI layer for the PMDG SOI LIGBT are nearly uniformly

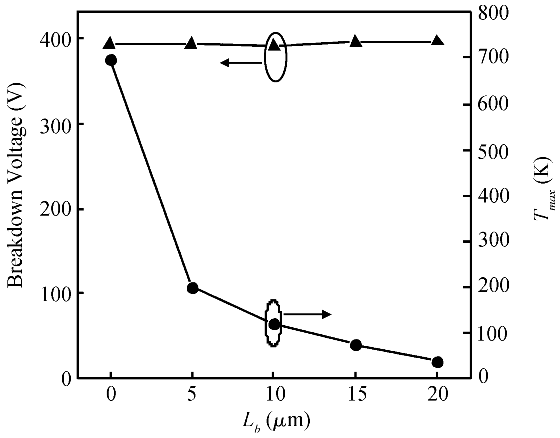

Fig. 7. Influences of L_b on T_{max} and BV.

distributed as illustrated in Figs. 6(a) and 6(b), which avoids premature breakdown, and therefore, enhances the blocking capacity. Two factors help to achieve the nearly ideal surface field distribution and the equi-potential contours for the PM DG SOI LIGBT. One is the partial removal of the substrate, which avoids collecting the charges below the buried oxide layer. The charges prevent the potential lines extending below the buried oxide layer and thus lead to electric field crowding in the SOI layer under the drain and a low breakdown voltage, as illustrated in Fig. 6(c) for the conventional SOI LIGBT. However, for the PM DG SOI LIGBT, the potential lines release deep below the membrane without these charge shielding effects and a high BV is therefore achieved. The other factor is the combination of uniformity and variation in lateral doping profiles in the drift region, which increases the avalanche BV and reduces $R_{sp.on}$.

Figure 7 gives the influences of L_b on BV as well as the maximum temperature T_{max} at a power of 0.5 mW/μm. The bottom of the substrate of 300 K and $V_{Cg} = 10$ V and $V_{Ag} = -5$ V are defined in a simulation of thermal characteristics. The thermal flow is directed away from the membrane area through silicon pillars to the package heat-sink attached to the bottom of the substrate. It is difficult to direct the thermal flow away from the membrane area for the CamSemi LIGBT because of the low heat conductivity of the thick air under the membrane. The temperature for the PM DG SOI LIGBT is lower than that of CamSemi due to the long silicon pillars and the lower $R_{sp.on}$. Figure 7 indicates that T_{max} for the PMDG SOI decreases with an increase of L_b due to a widened heat conduction path while the breakdown voltage almost remains constant.

4. Conclusions

A new power device structure of a PM DG SOI LIGBT is proposed. Firstly, its breakdown voltage increases by one time compared with the conventional LIGBT. Secondly, the proposed structure exhibits the high current capability and low $R_{sp.on}$ due to the combination of uniformity and variation in lateral doping profile. Thirdly, the absence of drain–substrate capacitance caused by the removal of the Si substrate under the drain–side results in a high swithing speed. Lastly, in comparison with the CamSemi LIGBT, a reduced self-heating effect is obtained due to the long silicon pillar for the PM DG LIGBT.

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